The Laser Interferometer Space Antenna Mission[1][2]

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Abstract—The Laser Interferometer Space Antenna (LISA) mission is designed to detect and study low-frequency gravitational radiation. The types of exciting astrophysical sources potentially visible to LISA include extra-galactic massive black hole binaries at cosmological distances, binary systems composed of a compact star and a massive black hole, galactic neutron star-black hole binaries, and background radiation from the Big Bang. LISA will also observe galactic binary systems which are known to exist.

1. Introduction

Gravitational waves are one of the fundamental building blocks of our theoretical picture of the universe. There is clear indirect evidence of their existence. The best example is the binary pulsar PSR 1913+16, a system that has been followed in its evolution for almost 20 years [1]. The binary system is losing energy at exactly the rate predicted by general relativity due to the emission of gravitational waves. However, direct detection of gravitational radiation signals has not yet been achieved.

The effect of a gravitational wave passing through a system of free test masses is to create a strain in space that changes distances between the masses. The main problem in observing gravitational waves is that the relative length change is exceedingly small. Several ground-based laser interferometers with arm lengths of several kilometers are now under construction. These detectors will use laser interferometry to measure changes in the distances between isolated proof masses. Because it is impossible to isolate proof masses from the slowly varying gravitational potential of the Earth, it will be impossible for ground-based detectors to observe low-frequency gravitational waves (frequencies below ~1 Hz).

LISA will complement ground-based gravitational-wave observatories by observing low-frequency gravitational waves with frequencies from 0.0001 Hz to 1 Hz. Previous searches for low-frequency gravitational waves have been made using Doppler measurements to interplanetary spacecraft. The Cassini project will include a special radio system to achieve a one order of magnitude improvement in gravitational-wave sensitivity compared with previous measurements. LISA will have six orders of magnitude greater sensitivity than the Cassini gravitational-wave experiment.[2]

2. Mission Overview

The LISA mission (Fig. 1) will comprise three spacecraft located 5×10^6 km apart forming an equilateral triangle. The spacecraft orbits are selected such that the triangular formation is maintained throughout the year with the triangle appearing to rotate about the center of the formation once per year. The center of the triangle formation will be in the ecliptic plane 1 AU (150×10^6 km) from the Sun and 20° behind (52×10^6 km) the Earth. LISA will detect gravitational wave strains down to a level of order 10^{-23} in one year of observation time by measuring the fluctuations in separation between shielded test masses located within each spacecraft. The LISA science objectives require measurements of the changes of distance between test masses separated by 5×10^6 km with picometer precision over a frequency range of 0.0001 Hz to 1 Hz.

The measurements will be performed by optical interferometry which will determine the phase shift of laser light transmitted between the test masses. Each test mass will be shielded from extraneous disturbances (e.g., solar pressure) by the spacecraft in which it is accommodated. Each spacecraft will contain two optical assemblies, each of which in turn will house a test mass centered in an optical bench and a 30-cm diameter telescope. Each telescope can act as the vertex of a two-

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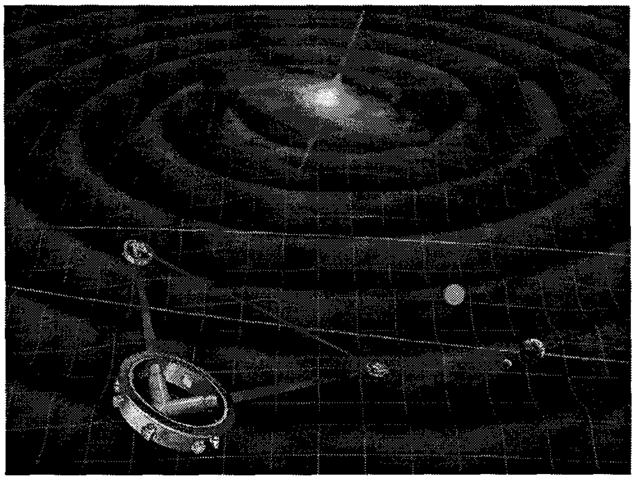

Figure 1. Artist's concept of the LISA configuration. Three spacecraft form an equilateral triangle with sides 5 million km in length. The plane of the triangle is tilted by 60° out of the ecliptic. The two optical assemblies on one spacecraft combine with an optical assembly from each of the other two spacecraft to form a Michelson interferometer.

arm interferometer with ends defined by a single optical assembly on each of the other two spacecraft. Of the three possible interferometers, two are independent giving information about both polarizations of received gravitational waves. At each spacecraft, the relative displacement between the spacecraft and the two test masses will be measured electrostatically. Micro-Newton thrusters will be operated to keep the spacecraft structure centered on the average position of the two test masses. This drag-free operation reduces non-gravitational forces on the test masses to an acceptable level.

Data on the measured distance between the test masses will be continuously acquired throughout the mission. Pre-processing of the data will be done by the spacecraft computer to remove the laser phase noise and reduce the signal bandwidth. The processed data will be stored in the spacecraft computer memory. The current plan is for the data to be transmitted to Earth once per week. A single 10 hour tracking pass of a Deep Space Network (DSN) 34-m antenna will be used to download both science and housekeeping data from each spacecraft.

Figure 2 shows a cross section of one optical assembly including the test mass and the transmit/receive telescope. An optical bench surrounding the test mass contains injection, detection and beam-shaping optics. The laser beam is carried to the optical bench within each optical assembly by an optical fiber. A few mW is split off the 1 W main beam to serve as the local reference for the heterodyne measurement of the phase of the incoming beam from the far spacecraft. Also, a few mW is split off and directed towards a triangular cavity which is used as a frequency reference. The incoming light from the telescope is reflected off the proof mass and superimposed with the local laser on the phase-measuring diode. A small fraction (a few mW) of the laser light is reflected off the back of the proof mass and sent for phase-comparison with the other optical assembly via an optical fiber. By bouncing the laser beams off the proof mass in the manner described, the interferometric measurement of proof mass position is, to first order, unaffected by motion of the surrounding spacecraft.

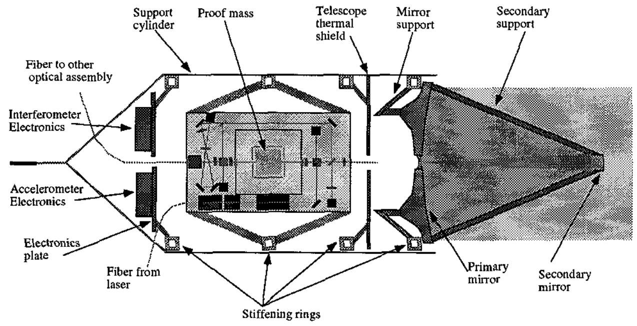

Figure 2 Cross section of one of the two optical assemblies comprising the main part of the payload on each LISA spacecraft.

The major LISA technology challenge is to sufficiently isolated the test masses from non-gravitational forces. The desire to measure distance changes, due to gravitational waves, of order 10 picometers means that the non-gravitational forces on the proof masses need to produce accelerations less than 3×10^{-16} m/s^2 r.m.s. at a frequency of 10^{-4} Hz. This level of performance cannot be established in laboratory testing, since extremely small changes in instrument orientation variably couple in the ~10 m/s^2 acceleration due to the Earth's gravity. The best laboratory performance achieved for a complete inertial sensor, over the frequency range of interest for LISA, is ~10^{-10} m/s^2/√Hz. However the types of noise forces that can affect the inertial sensor proof mass can be identified and separately characterized in laboratory tests. Based on the noise models and tests, detailed instrument designs for inertial sensors meeting the LISA requirements have been completed. Because the LISA requirements are far beyond what can be achieved in the laboratory, it is highly desirable to have a space flight experiment to demonstrate that the performance specifications can be met.

Many of the noise forces on the proof mass are affected by fluctuations in the distance between the proof mass and the rest of the spacecraft. For example, the spacecraft mass has a gravitational pull on the proof mass and thus fluctuations in the position of the spacecraft cause fluctuations in the force on the proof mass. Because of this the position of the spacecraft must be controlled to stay centered on the proof mass. The position control requirements, derived from the inertial sensor requirements, in turn place requirements on the spacecraft thrusters. With the current mission design, the thrusters are required to have a thrust noise of about 0.1μN, with a continuous thrust of about 25 μN in order to oppose the force from solar radiation pressure. The best candidate thrusters for meeting these requirements are based on emission of ionized metal (Cs or In) atoms accelerated by an electric field. These thrusters have been under development for many years, originally with the idea of more efficiently performing attitude control for commercial satellites.

Measurement of changes of distances between proof masses is routinely done with laser interferometry. For ground-based gravitational wave detectors, techniques for measuring distance changes of order 10^{-19} m have been developed and demonstrated over the past 20 years or more. However, interferometers for ground-based gravitational-wave detection have been optimized for motions at much higher frequencies than desired for LISA, and at much higher laser signal powers. The LISA measurement band, and many of the technological challenges, are perhaps more similar to spacecraft Doppler tracking which uses radio signals to measure changes between the Earth and interplanetary spacecraft, which is a technique which has been used to look for low-frequency gravitational waves. Like Doppler tracking, LISA will transmit and receive signals, albeit at optical rather than radio frequencies, between pairs of antennas and use heterodyne mixing of signals to measure Doppler shift. By being outside the Earth's atmosphere, and by using much higher transmission frequencies, LISA will not be affected by fluctuations in the transmission media (Earth's troposphere and ionosphere, and solar plasma) that are one of the limiting errors sources for Doppler tracking. And like ground-based interferometers, and unlike Doppler tracking experiments, LISA will use two pairs of transmitter/receiver satellites, synthesizing a two-arm Michelson interferometer, to cancel the noise due to frequency fluctuations of the transmission signal, to achieve the desired sensitivity.

3. CONCLUSION

LISA is an integral mission in the Cosmic Journeys initiative. Cosmic Journeys is part of NASA's Structure and Evolution of the Universe space science theme. When funded, Cosmic Journeys will combine the science in astrophysics and fundamental physics. The initiative includes scientists from NASA, Department of Energy, and the National Science Foundation.

ACKNOWLEDGEMENT

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REFERENCES

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[2]More information can be found at the LISA web site, http://lisa.jpl.nasa.gov.

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